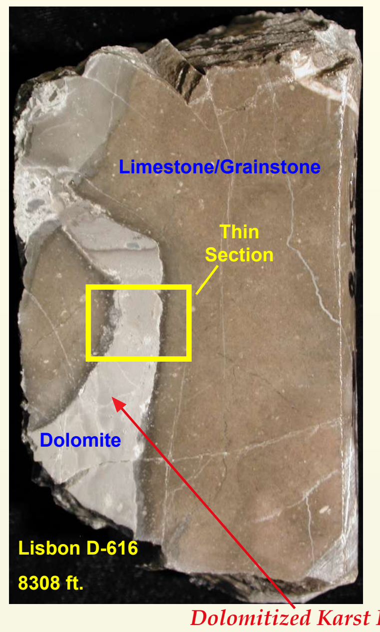
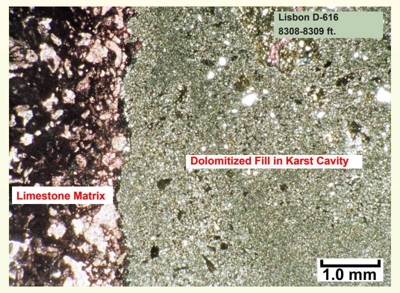
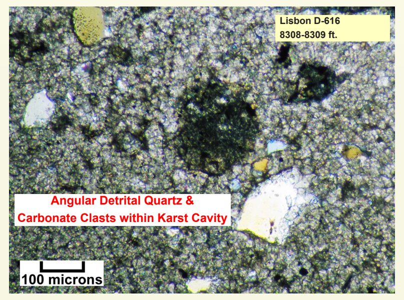
Karst-Related Processes



Sediment-filled cavities are relatively common throughout the upper third of the Leadville in Lisbon field. These cavities were related to karstification of the exposed Leadville. Infilling of the cavities by detrital carbonate and siliciclastic sediments occurred before the deposition of the Pennsylvanian Molas Shale. The carbonate muds infilling the karst cavities were largely dolomitized.

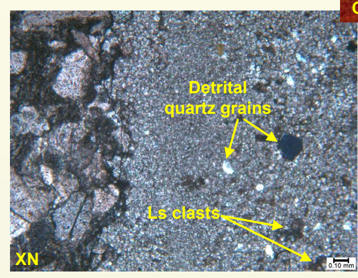


Low magnification micrograph under plane light showing the contact between the non-porous limestone matrix and the non-porous dolomitized and siliciclastic karst-cavity filling.



Higher magnification of detrital quartz grains (white) and small carbonate clasts (dark gray) within the tight, dolomitized mud filling the karst cavity.

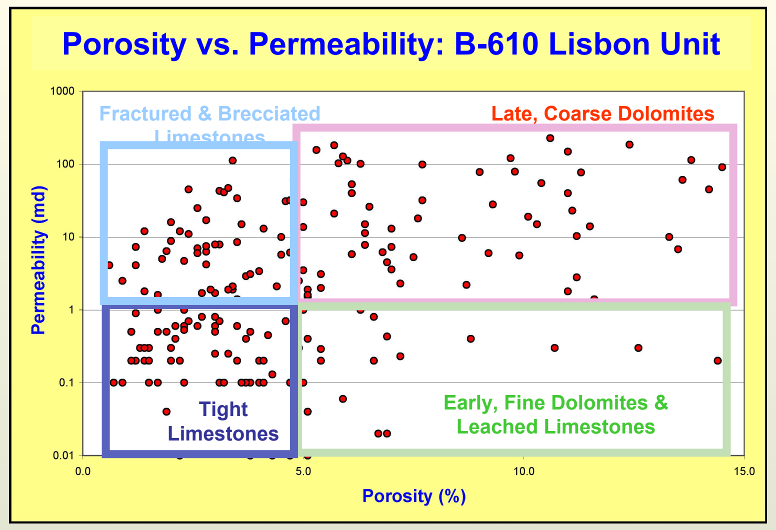
Catholuminescence of Dolomitized Karst Filling



Lisbon D-616

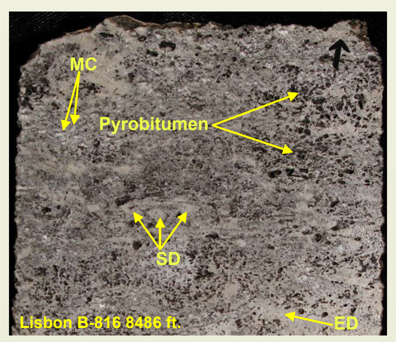
8308 ft.

The upper right micrograph shows the contact between the limestone matrix (in dark red) and the dolomitized karst filling (in red) under catholuminescence (CL). Note that the dolomitized filling is composed of very fine crystals displaying uniform red CL colors. The identical view under crossed nicols (XN) is shown in



This representative set of core analyses from Leadville dolomites shows two distinct populations of dolomites with respect to permeability and petrographic character. The early, finely crystalline dolomites (with or without isolated molds) display low permeability. The coarser late dolomites (with or without late dissolution) display high permeability. Some of these highly permeable dolomites are shown in the photos below.

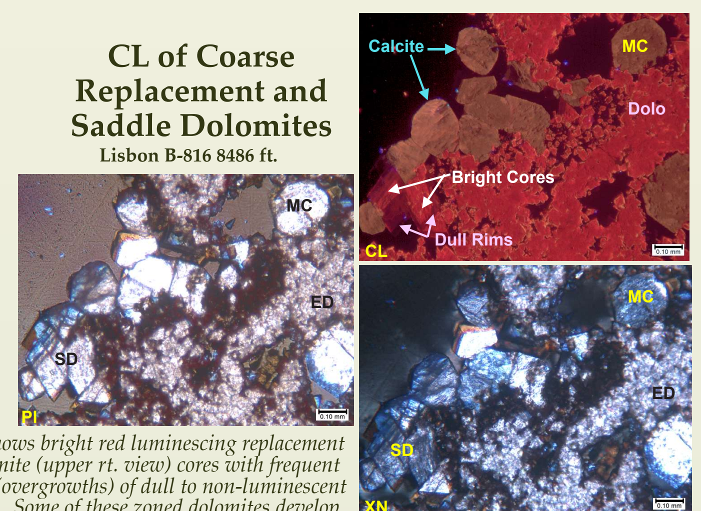
Coarse Replacement and Saddle Dolomites



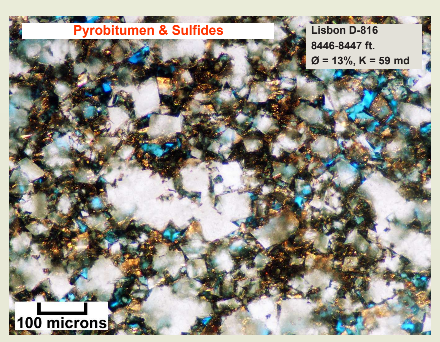
Conventional core surface showing a typical interval in which fabric selective, early dolomite (ED) is replaced by much coarser, rhombic dolomites (with excellent permeability). Some replacement dolomites also display saddle dolomite (SD) morphologies. Most of the coarser dolomites are lined with thin films of black pyrobitumen. A few dissolution pores are filled with post-coarse dolomite macrocalcite (MC) cements.

CL of Coarse Replacement and Saddle Dolomites

Lisbon B-816 8486 ft.



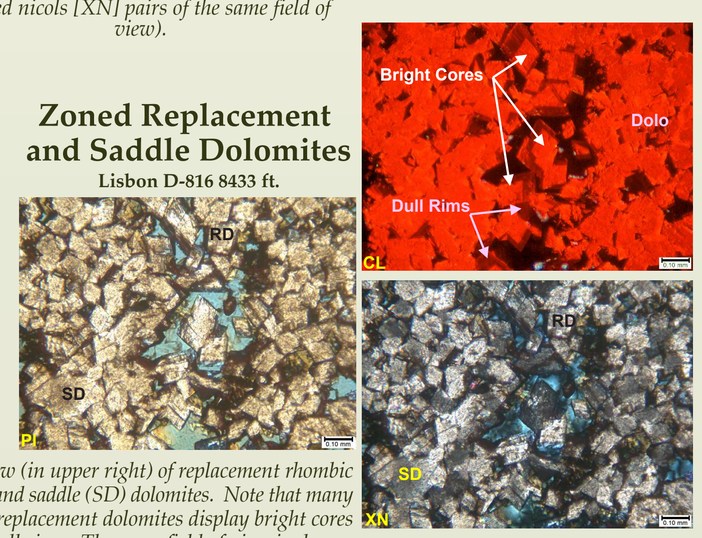
CL shows bright red luminescing replacement dolomite (upper rt. view) cores with frequent rims (overgrowths) of dull to non-luminescent rims. Some of these zoned dolomites develop "saddle" characteristics (see plane light [PI] & crossed nicols [XN] pairs of the same field of view).



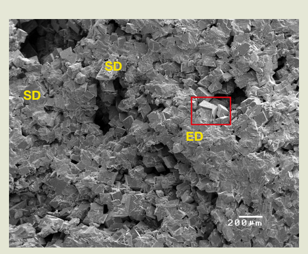
Thin section micrograph under "white card" and reflected light showing black pyrobitumen and sulfide minerals on and between rhombic dolomite crystals (in white and light gray).

Zoned Replacement and Saddle Dolomites

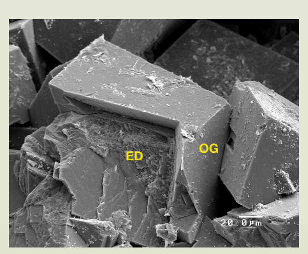
Lisbon D-816 8433 ft.



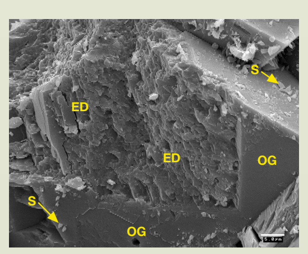
CL view (in upper right) of replacement rhombic (RD) and saddle (SD) dolomites. Note that many of the replacement dolomites display bright cores and dull rims. The same field of view is shown under plane and crossed nicols light.



A



B



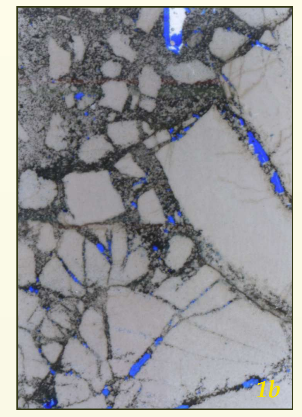
C

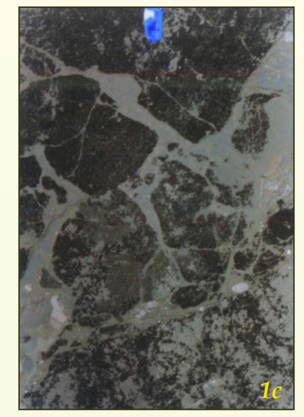
A. Low magnification SEM showing typical Leadville dolomites at Lisbon field. Note the very fine, tight early dolomites (ED) that have been replaced with late rhombic and saddle (SD) dolomites. There is significant porosity increase associated with the late dolomite replacement. Red box = B.

B. This closer view shows the composition of typical replacement rhombic dolomites. The core of each rhombic crystal is composed of a dense remnant of fine, early dolomite (ED) which is surrounded by a euhedral dolomite overgrowth (OG). The rhombic dolomite faces are often covered with a thin film of pyrobitumen.

C. High magnification SEM across a section of a poorly crystalline, early dolomite core (ED) and a dense overgrowth (OG) that forms the dolomite into coarser rhombs. The very small angular decorations on the crystal surfaces may be very small sulfide precipitates (S).

Post-Burial Brecciation, Dissolution & Cements



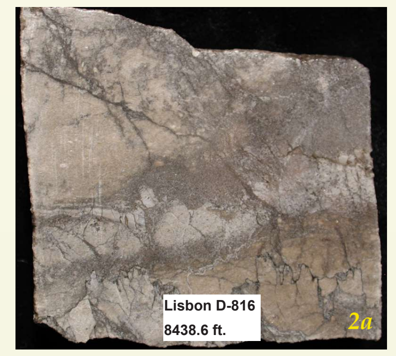


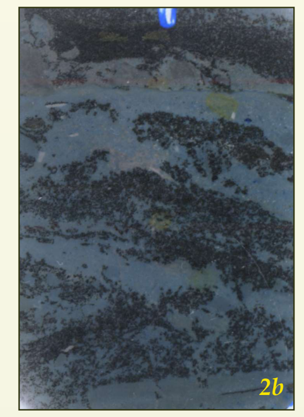
Fracturing and brecciation are quite common in late dolomites within Lisbon field.

1a. Core photo showing a dolomite "autobreccia" in which the "clasts" have moved very little. The black material surrounding the in-place "clasts" is composed of porous late dolomite coated with pyrobitumen.

1b. Entire thin section overview of low-porosity white dolomite clasts surrounded by solution-enlarged fractures partially filled with coarse rhombic and saddle dolomites that are coated with pyrobitumen. These black areas between the clasts exhibit very good intercrystalline porosity. The open fracture segments (in blue) between clasts are bridged by coarse saddle dolomite cements.

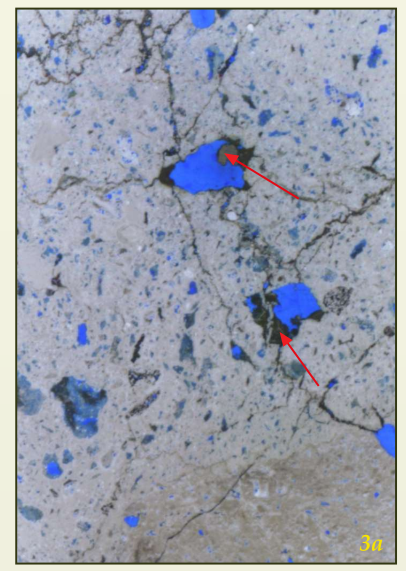
1c. Entire thin section overview of black, porous dolomite clasts that are surrounded in this case by coarse, low-porosity saddle dolomites. These white dolomites were probably filling space between possible "hydrofractured" replacement dolomites. The black porous dolomites are mostly rhombic (planar) dolomites coated with thin films of pyrobitumen.

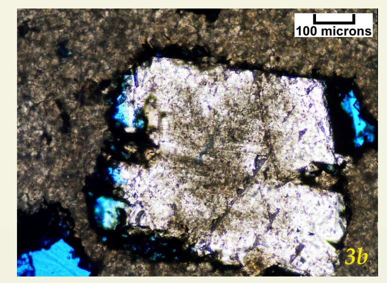


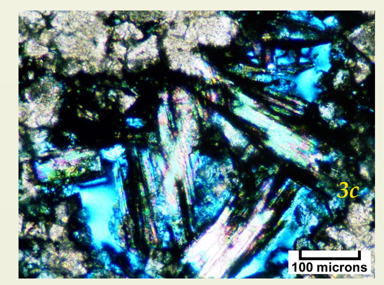


2a. Core photo showing a dolomitized interval with distinct white and dark gray to black banding which crudely resembles "zebra structure." The white portions of this rock are tight replacement dolomites while the dark gray and black areas are porous rhombic and saddle dolomites lined with pyrobitumen films. In addition, note the swarms of fractures marked by black, porous dolomite.

2b. Entire thin section overview of micro-banded bluish white and black dolomites that has the appearance of small scale "zebra structure." The black bands consist of porous, coarse dolomites (both rhombic and saddle varieties) that are coated with thin films of bitumen. The bluish white bands are composed of coarse dolomite and late calcite with some microporosity.



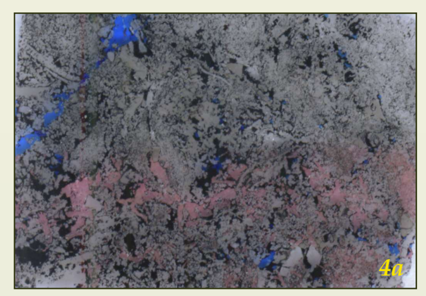




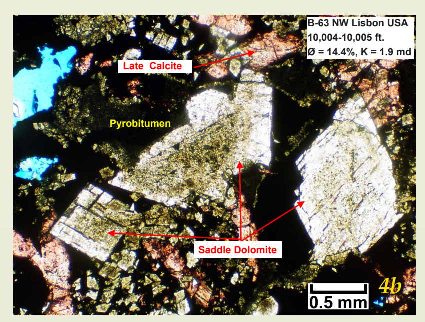
3a. Entire thin section overview of dolomite that has experienced significant amounts of late dissolution. The brownish areas at the base of the slide are remnants of early, very finely crystalline dolomite. The remaining white areas are much coarser late dolomites and some late calcite. Dissolution of both types of dolomite has resulted in solution-enlarged molds and small vugs (in blue). In addition, there is dissolution along stylolites and fractures. This dissolution event post-dates all of the stylolite and fracture generation in this dolomite. Sulfide minerals (see arrows) are precipitated within some of the larger pores.

3b. Thin section photomicrograph under plane light showing a saddle dolomite cement that is filling a large pore (either a grain mold or small vug). The dolomite cement has been surrounded by a coating of pyrobitumen (in black). It appears that this late dolomite cement has been partially dissolved or corroded around its margins after the bitumen coating.

3c. Thin section photomicrograph under cross-polarized light showing lathes of late anhydrite cement (in the pastel colors) filling a dissolution pore. The unfilled portions of the pore are seen in the blue areas.



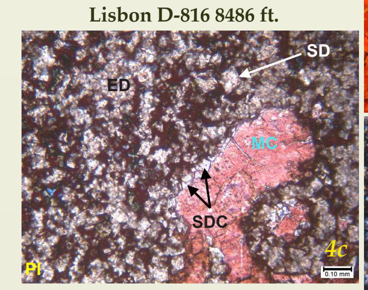
4a. Entire thin section overview of a typical skeletal calcarenite that has been replaced by dolomite. Much of this dolomite is coarsely crystalline with rhombic and saddle habits. Most of the coarse dolomites have been coated with black pyrobitumen. Note that there are multiple stages of dolomite dissolution. One generation of leaching has been partially filled with late macrocalcite cement (in red). Additional dissolution along fractures and stylolites can be seen in the blue areas.

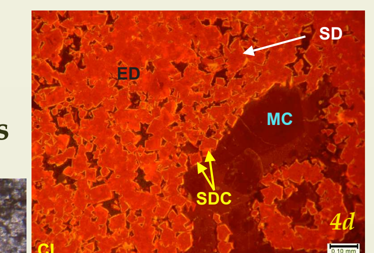


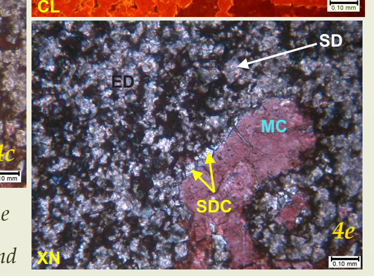
4b. Thin section photomicrograph under plane light from the same sample shown above (4a). Note the coarse rhombic and saddle replacement dolomites that display cloudy cores and clear rims. Dissolution pores are filled with pyrobitumen (black) and late macrocalcite (red). An additional episode of dissolution can be seen as the open (blue) pores that appear to post-date most of the pyrobitumen emplacement.

CL of Replacement and Saddle Dolomites

Lisbon D-816 8486 ft.





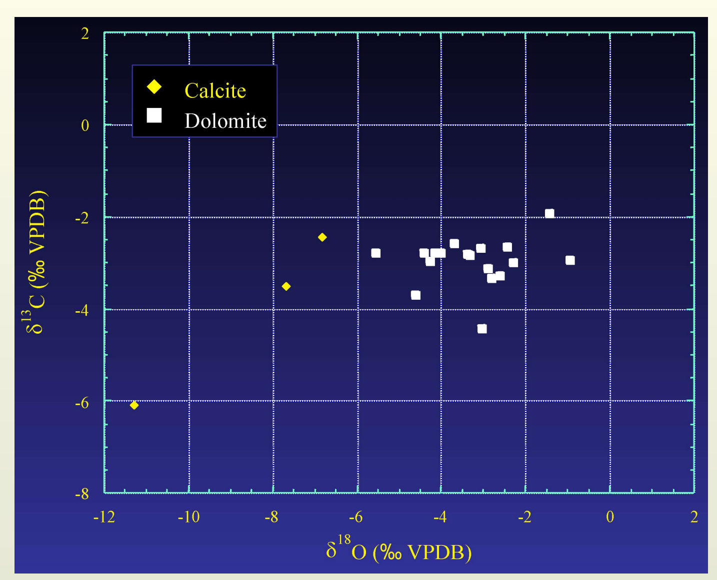


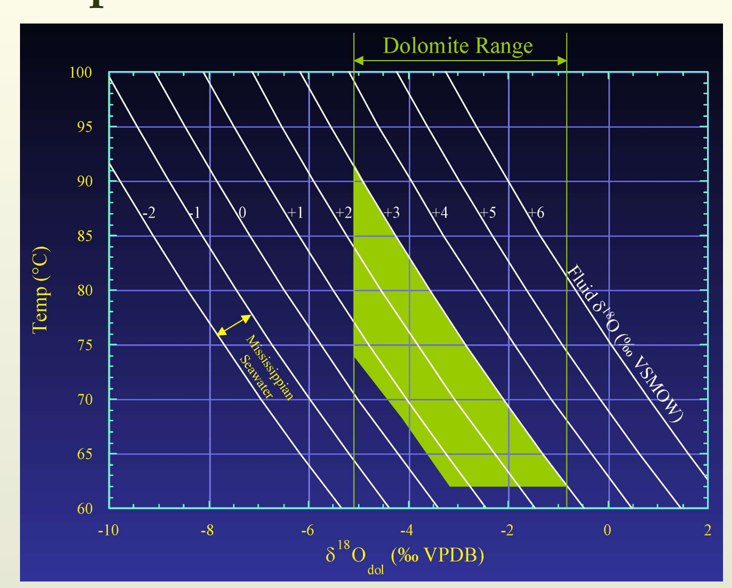
4c. Thin section photomicrograph under plane light showing dolomitized matrix rocks (with remnants of early fine early dolomites (ED) and coarser late dolomites which are composed of rhombic and rare saddle crystals. Dissolution pores are lined with saddle dolomite cements (SDC, see arrows) followed by a later macrocalcite cement (red areas, labeled MC).

4d. CL view of same area as in 4c, showing the bright red luminescence of the majority of the matrix replacement dolomites. Many of the coarser dolomite crystals have dull to dead final growth zones. The late macrocalcite cements exhibit dull orange luminescence.

4e. Thin section photomicrograph under cross-polarized light showing the same field-of-view as 4c and 4d. In this micrograph, the extinction and shape characteristics of some of the late replacement and pore-filling dolomites can be seen.

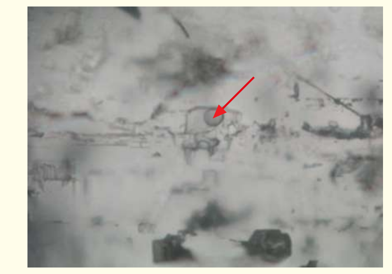
Stable Isotopes





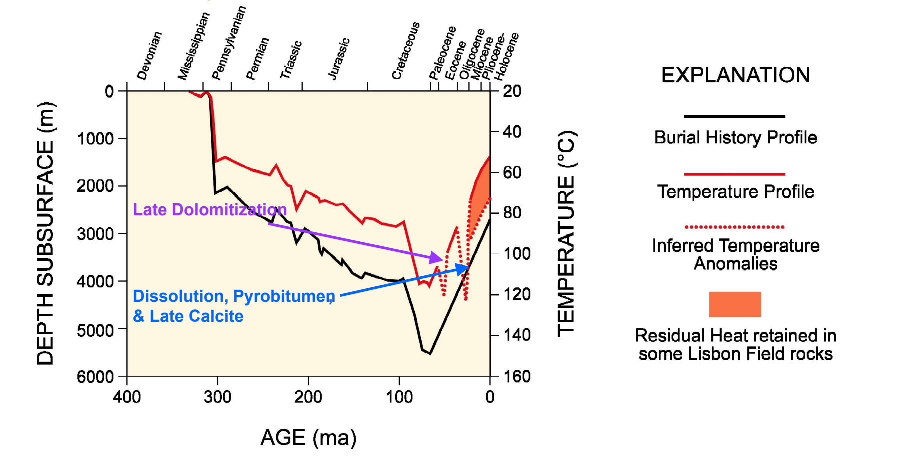
Stable oxygen isotope analyses of dolomites show a linear trend with a fairly narrow range of carbon isotope values. Dolomitzing fluid compositions with respect to del O^{18} are thought to be heavier than normal Mississippian sea water (bracketed by the yellow arrows on the right graph). The green field on the right figure shows our estimate of del O^{18} of dolomitizing fluids at between 0.5 and 3.0‰. Precipitation temperatures were up to ~90°C.

Fluid Inclusions

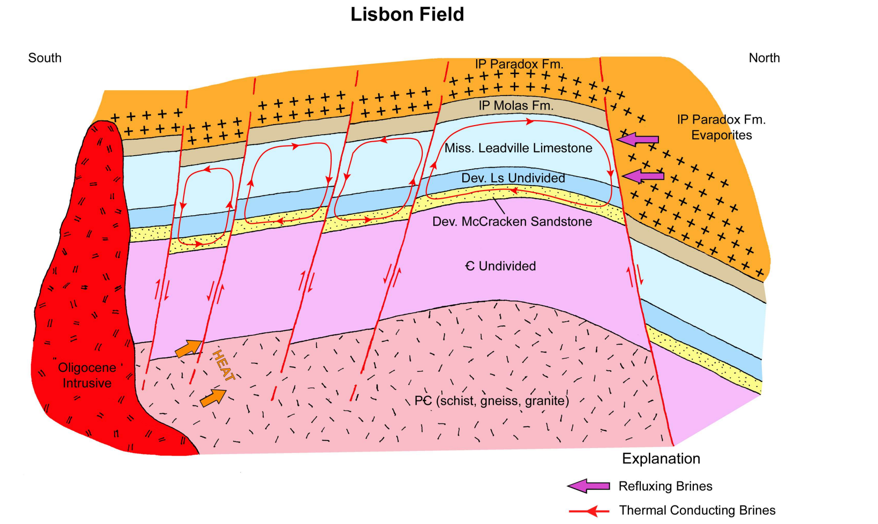


Two-phase fluid inclusions (similar to the one indicated by the arrow above) have been measured in the zoned rhombic and saddle dolomites as well as in late calcite cements. The final growth zones in the dolomites yield homogenization temperatures of 138-188°C. The late calcites yield minimum temperatures of 153-220°C. Inclusions from both dolomites and calcites contain saline fluids (~2-3x seawater).

Burial History and Temperature Profile with Two Inferred Hydrothermal Events at Lisbon Field



Conceptual Diagram Showing Convection Cells & Possible Heat Sources for Late Dolomitization & Dissolution



Conclusions

- Leadville reservoir quality at Lisbon is greatly enhanced by dolomitization and dissolution of shallow water limestones
- Early dolomitization:
  - Preserves depositional fabrics
  - No porosity development, except for limited dissolution of fossils
  - Very low permeabilities
- Late (deep subsurface) dolomitization
  - Two morphologies:
    - Rhombic dolomites (100 – 250 μ diameter)
    - Saddle dolomites (>200 μ)
- Porosity and permeability development by:
  - Post-stylolitization & post-fracture replacement dolomitization to form coarse rhombic and saddle dolomites
  - Major dissolution of limestones and early dolomites along fractures
- Late cements in dissolution pores and fractures
  - Saddle dolomites
  - Megacalcite spars
  - Minor megaquartz
  - Anhydrite cements
- Evidence for hydrothermal dolomitization
  - Saddle dolomite replacement and cements
  - Occasional zebroid fabrics
  - Co-associated late dissolution of limestone, dolomite, & chert
  - Pyrobitumen and sulfide mineralization
  - Preliminary stable isotope data (up to 90°C) and two-phase fluid inclusions (homogenization temperatures of 138-188°C for last dolomite growth zone and 153-220°C for late calcites)
- Two hydrothermal events possible:
  1) Late Laramide reactivation along normal faults, resulting in trap formation, access to brines from Pennsylvanian evaporites, and dolomitization to zoned

Acknowledgments

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